Mass Balance of Multiyear Sea Ice in the Southern Beaufort Sea

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LONG-TERM GOALS

1) Determination of the net growth and melt of multiyear (MY) sea ice during its transit through the southern Beaufort Sea
2) Identification of key regional processes in southern Beaufort Sea affecting MY ice recruitment
3) Improved predictability of the future states of the Arctic ice pack

OBJECTIVES

We have four main scientific objectives:

I) Estimation of MY ice volume entrained into the Beaufort Sea from north of Canada
The region north of the Canadian Archipelago contains some of the oldest and thickest ice in the Arctic and the amount of this ice imported into the Beaufort Sea has a significant effect on the overall MY ice budget of the Arctic.

II) Estimation of rate of thinning of MY ice during transit through southern Beaufort Sea
The thickness of MY ice at the end of its westward transit through the Beaufort Sea will have a critical impact on the volume of MY ice recruited from one year to the next and on navigability in the Beaufort and other marginal seas.

III) Assessment of contribution of refreezing of meltwater to overall mass balance of MY ice
Meltwater created through surface ablation can refreeze if it finds its way underneath the sea ice where the ocean will typically be at the colder freezing point of seawater. This can create ice lenses and false bottoms beneath the sea ice and make a positive, but poorly-understood, contribution to the mass balance

IV) Assessment of the role MY ice dispersal in promoting ice loss
We speculate that diminished MY ice in the Beaufort Sea may be a consequence of changes in drift patterns. Moreover, if net drift and divergence increase as MY ice extent decreases, this may represent a feedback process that will accelerate the Arctic's trajectory toward a seasonally ice free state.

APPROACH

To address our four main scientific objectives, we are employing a data fusion approach using a range of public-domain in-situ and remote sensing datasets. Through the methods described below, we aim to identify and quantify regional feedbacks between ice dynamics and mass balance, which will be critical in the predictability of ice conditions of timescales of 5-10 years.

Beaufort Sea flux gates (Hutchings and Mahoney)

As one step toward addressing objective I, we have analyzed buoy drift data to determine areal flux of sea ice entering and exiting the Beaufort Sea through "gates". This works build upon previous analysis by Hutchings and Rigor [2012] and is the subject of another paper currently in preparation by Petty et al. We will extend these results by combining them with satelite-derived ice age data [*Maslanik et al.*, 2007] to focus on the areal flux of multiyear passing through these gates. Deriving the volume flux of MY ice will be more challenging as observational ice thickness data are sparse. However, we will make use of airborne electromagnetic (AEM) data from the Tuktoyaktuk and Barrow regions to examine differences in the thickness of ice entering and leaving the southern Beaufort Sea, which will also address objective II.

Repeat passes of ice over moored IPSs (Mahoney)

In addition to the flux gate approach described above, we are also tracking changes in MY ice thickness in the southern Beaufort Sea (Objective II), through a combined Eulerian-Lagrangian approach that identifies cases when drifting ice makes multiple passes over moored ice profiling sonars (IPSs). In earlier work on this project, we analyzed data from the International Arctic Buoy Program (IABP) over the period 2003-2012, and identified 12 buoys that repeated passes within 30 km of one or more of four IPS-equipped moorings deployed as part of the Beaufort Gyre Exploration Project (BGEP). This demonstrates that such events are sufficiently commonplace to allow a Lagrangian analysis of ice thickness changes over time in the Beaufort Sea. We are also extending this analysis using numerical buoys, which we track using Fowler *et al.*'s gridded ice velocity product [*Fowler et al.*, 2013], which we refer to as the FGIV dataset.

Analysis of melt processes from ice core and IMB data (Eicken)

Through stratigraphic analysis of sea ice cores collected from the Beaufort and Chukchi Seas as part of the Seasonal Ice Zone Observing Network (SIZONet), we identify annual layers that help constrain the age of the ice. In combination with ice drift data, this will allow us to estimate the origins of MY ice in the Beaufort Sea. Ice core samples that are brought back to shore were melted and used to determine profiles of salinity and stable isotope ratios. These data allow us to identify layers of refrozen melt water that once pooled beneath the ice. These meltwater layers, traces of which are found in all multiyear ice cores, form part of the annual accretionary layers and contribute to the total mass budget of level ice in the region. Identifying such layers will help interpretation of data from ice mass balance buoys (IMBs), which may overestimate ice thickness in the presence of false bottom or under-ice melt ponds. In addition, we can draw on mass balance data from Ice Mass Balance buoys (IMBs) to identify the potential impact of underwater ice formation on the seasonal mass budget. These analyses will be fundamental to achieving objective III.

Analysis of thickness changes in context of ice deformation (Hutchings)

Ice dynamics play a complex role in the overall mass balance of sea ice in the Beaufort Sea [e.g., *Hutchings and Rigor*, 2012]. We expect to gain some insight into these processes (Objective IV) though analysis of the tails of ice thickness distributions corresponding to repeat overpasses of moored IPSs. However, it is not clear that the current observing assets are capable of resolving ice motion with sufficient fidelity to resolve to lead creation and ridging rates. With this in mind we are investigating the utility of remotely sensed ice drift products in providing deformation fields. We used divergence and shear from drifting buoy arrays to ground truth two representative satellite-derived ice velocity products: the Radarsat Geophysical Processor System [RGPS; *Kwok*, 1998] and the daily gridded ice velocity product produced by Fowler *et al. [2013].* These products allow us to investigate the effects of sampling rate, position accuracy and spatial resolution on the ability to monitor sea ice deformation. Following Lukovich *et al.* [2014], we are also developing approaches to map dynamical regimes along buoy tracks. These regimes range from super-diffusive conditions, where ice is advected and organized structures are preserved, to sub-diffusive, where ice-ice interactions dominate.

WORK COMPLETED

Expanded analysis of Lagrangian "pseudo-plumes"

Utilizing techniques developed previously, we used the FGIV data to estimate the drift track of sea ice originating daily at each of the four moorings in the Beaufort Gyre Exploration Project (BGEP). This allowed us to identify occasions when there was a high probability that sea ice passed from one mooring another in what we term an inter-mooring advection event (IMAE). Figure 1 illustrates four IMAEs that occurred in different years and at different times of year between each of the four BGEP moorings. Between 2003 and 2012, we identified 123 such events. The significance of IMAEs is that they offer the opportunity for repeat observations of the thickness of the same patch of ice as it drifts through the Beaufort Sea, since each mooring is equipped which an ice profiling sonar (IPS).

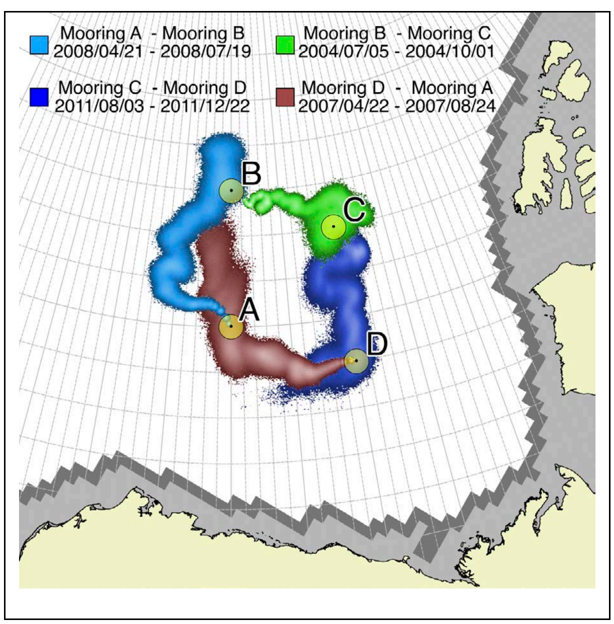

Figure 1: Illustration of four different inter-mooring advection events (IMAEs) between each of the BGEP moorings

Using a similar approach, we have also calculated back- and forward-trajectories of sea ice at different points along the flight tracks of airborne electromagnetic (AEM) ice thickness surveys. This will assist us in calculating the volume flux of ice transported across the Beaufort Sea. Ice observations made during the AEM flights will allow us to identify regions of MY ice along the survey lines.

<u>Assessment of ice velocity and lead data products for analysis of ice deformation and mechanical properties</u>

We have continued to analyze Radarsat Geophysical Processor System (RGPS) and FGIV datasets to assess their suitability for quantifying ice deformation in the Beaufort Sea. Selection of the appropriate dataset and a complete understanding of the relevant uncertainties will be essential for analyzing the relationship between the mass balance and dynamics of a thinning ice cover in the Chukchi Sea. We have also started to examine an extensive set of lead data for the southern Beaufort Sea derived from AVHRR imagery for the period period 1994-2010 [*Mahoney et al.*, 2012]. These will allow us to examine changes in lead fraction and distribution in relation to observed changes in ice thickness and drift velocity. We have also started developing an analytical approach to estimate mechanical properties of the ice cover based on the parabolic shape of leads.

<u>Analysis of ice core stratigraphy and IMB bottom data</u>

Due to co-I Eicken's recent appointment as Interim Director of the International Arctic Research Center, minimal progress has been made in this area of the project over the last twelve months. However, as we have been granted a 12-month no-cost extension on this award we hope to continue this work when Eicken resumes his regular faculty role.

<u>Planning of future activities during no-cost extension</u>

Due to co-I Eicken's new appointment and the delayed receipt of year 3 funds, we requested and were granted a 12-month no-cost extension on this award. We are planning to hold a project in November 2015 at York University, hosted by our no-cost collaborator Christian Haas, to discuss plans for final data analysis and preparation of manuscripts addressing the projects key objectives. We anticipate that Eicken will resume his regular faculty role during this period and continue his component of the research.

RESULTS

<u>Thickness changes during IMAEs</u>

For each of the 123 IMAEs described above, we have been able to extract pairs ice thickness distributions representing the thickness of 50 km-wide ice patches at the beginning and end of each event. By comparing the primary modes of the beginning and ending thickness distributions, we can assess changes in level ice thickness over the span of each IMAE. Figure 2 shows illustrates how these changes follow a clear annual cycle, but by color-coding IMAEs according to where they take place in the Beaufort Sea, it is clear that the southern Beaufort Sea (red) experiences greater thinning the northern Beaufort Sea (green). These results, together with results from analysis of repeat IPS observations of buoy-tracked ice was presented at the AGU Fall Meeting in San Francisco in December 2014.

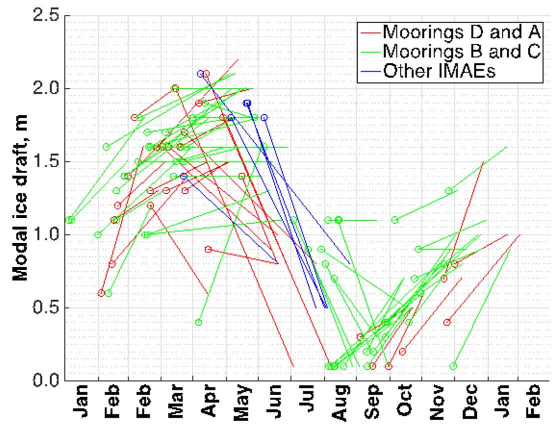

Figure 2: Changes in modal ice draft during IMAEs plotted against time of year. Each line represents one IMAE, with circles indicating the initial mode. Lines are color-coded according the moorings involved.

<u>Identification of ice patches observed by both IPS and AEM</u>

By applying pseudo-Langrangian tracking technique to all AEM data from the Seasonal Ice Zone Observing Network (SIZONet) and Polar Airborne Measurements and Arctic Regional Climate Model Simulation Project (PAMARCMIP) and Beaufort Regional Environmental Assessment (BREA) campaigns, we have identified three cases where there is a reasonable likelihood that sea ice measured by AEM had previously drifted within 25 km of one of the BGEP moorings. Figure 3 shows one of these cases, which indicates that sea ice in the central portion of the AEM survey flown on April 10, 2012 (red plume) drifted within 25 km of mooring D approximately 160 days previously in early November 2011. The significance of this example is that it represents the possibility of examining observing the wintertime changes in thickness of ice that survived the previous summer.

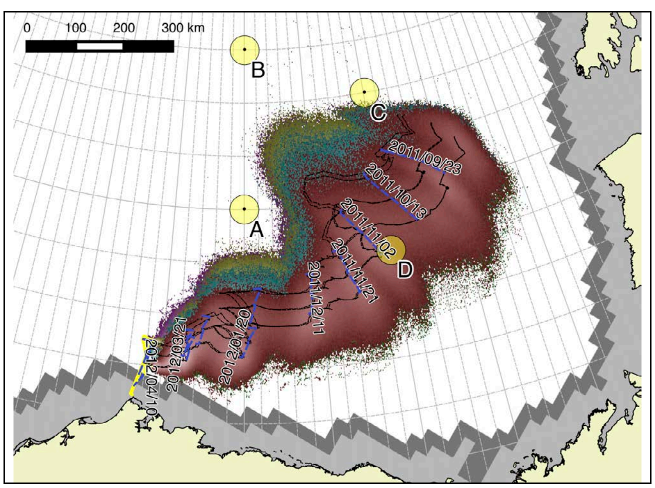

Figure 3: A series of pseudo-plumes indicating the back-trajectory of ice along an AEM survey flown from Barrow on April 10, 2012. Plumes are color coded according to point of origin along the AEM track. The black dashed lines indicate the mean path of each plume, while the blue dashed lines represent isochrones at 20-day intervals

IMPACT/APPLICATIONS

We anticipate our future results will improve understanding of the fate of multiyear sea ice in an increasingly seasonal ice pack and lead to reduced uncertainty in sea ice forecasting. In particular, by quantifying the roles of specific processes on the mass balance of MY ice in the Beaufort Sea, our work will highlight where key areas of undertainty remain. In addition, we are developing new techniques to utilize sea ice velocity measurements to study Lagrangian processes with Eulerian observations such as mooring data and AEM surveys. The work we reported on last year, demonstrated that tracking repeat IPS observations with buoys was feasible. Over the last twelve months, we have extended this work using numerical buoys increased the number of repeat IPS observations by an order of magnitude. In doing so, we have also laid the groundwork for a new methodology of integrating Eulerian components of ocean observing networks, which could also be a poweful tool for designing of future observing networks.

RELATED PROJECTS

PI Mahoney and co-I Eicken are leading the Seasonal Ice Zone Observing Network (SIZONet) project. Data from this project will provide additional calibration and validation data to interpret airborne electromagnetic induction and ice-profiling sonar from the region. The project also contributes ice thickness and ice core data sets analyzed in this study.

Co-I Hutchings is leading the NSF-funded project Sea Ice Deformation Observation with an AON, which is assessing the capabilities of the current Arctic buoy network to resolve sea ice deformation and designing a network of GPS-enabled buoys to short-timescale motion and deformation events.

PI Mahoney is participating in efforts funded by industry and the Bureau of Ocean Energy Management (BOEM) to deploy buoys on drifting ice in the Beaufort Sea, including specific efforts to track MY ice floes entering the Chukchi Sea.

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